ELECTRONIC DESIGN EXCLUSIVE

# Careful design takes the heat out of hybrid power op amps

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When circuits have to supply significant power to resistive and reactive loads, designers face a particularly tricky set of problems. Dedicated and discrete units are costly, occupy a lot of space, and take time to put together.

The solution to these disadvantages lies in the hybrid power operational amplifier, a useful device that wraps up the components needed for the job in a single package. Op amps greatly improve all-round reliability, cut down size and weight, and simplify assembly.

***Circuits that handle power can be easy to build. But designers must avoid overloads that cause dissipation to surge and, if unchecked, smoke to rise.***

But a designer cannot choose what op amp to use without thoroughly understanding the job at hand and the capabilities of the component. Whatever happens, the op amp cannot be pushed beyond the specifications detailed in the manufacturer's data sheet. Otherwise, surges in dissipated power may damage the op amp—possibly fatally, certainly to a degree that will shorten its life and diminish its usefulness.

The data sheet's absolute maximum ratings mark levels of stress that, taken one at a time, will not cause permanent damage. Problems can arise, however, if two or more such stress levels—such as maximum power and temperature—are exceeded simultaneously. Moreover, proper operation is only guaranteed over the specified ranges.

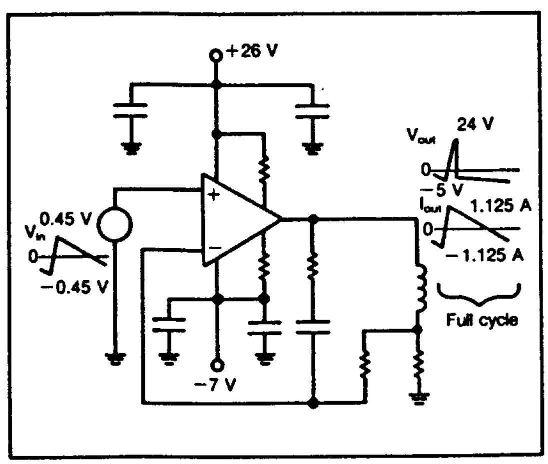
Most power amplifiers, for example, have an absolute case-temperature range of −55° to +125°C. If a circuit's design takes the op amp outside that range, it may latch on to one of its supply rails; and although latching usually causes no permanent damage, even that may happen if the condition violates the chip's safe operating area.

The accepted method of specifying maximum power dissipation provides a yardstick for comparing manufacturers' ratings. This procedure assumes that the op amp's case temperature is a steady 25°C and that the junctions are operating at the maximum rating. That maximum should not be considered reliable, however, since it assumes an ideal heat sink. At the maximum, even the best practical heat sink could allow the op amp to overheat and fail. Most manufacturers also recommend, therefore, that the junction temperature should never go above 150°C, regardless of what the data sheet says.

## CHECKING SPECIFICATIONS

The table of specifications is an engineer's principal guide to any component's applicability. Besides listing minimum and maximum values of such critical parameters as voltage offset and outputs, the table defines the guaranteed linear operating range in terms of common-mode voltage, input power, and temperature.

Graphs showing typical performance also help a designer determine how performance varies as spe-




**1. A high-current nonsymmetrical waveform, such as that produced by a television set's yoke driver, can be produced efficiently by a hybrid power op amp driven by two dc supplies, an arrangement that maximizes the op amp's output and reduces its heat dissipation.**

cific operating conditions change. A designer must bear in mind, however, that statistically only about half the individual components will work under circumstances based strictly on typical-performance graphs. The problem with such graphs lies in the one word, typical. Many production lots are sampled for typical-performance data, and any specific lot of, say, 100 devices could come from a single production run that may—or may not—perform in the way described in the graph.

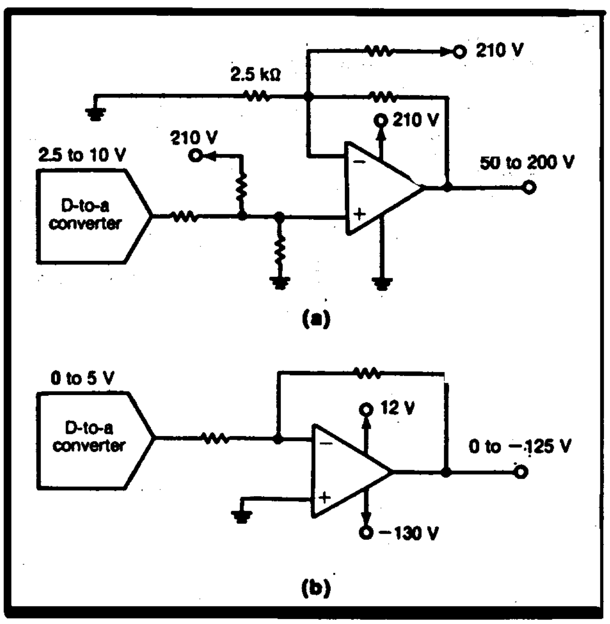
A designer has a number of choices in how to limit dissipation in the face of changing loads. Some situations call for parallel amplifiers, some for delayed switching time, some for a bridge configuration.

For a power op amp to deliver its maximum output efficiently, dissipated power should be kept to a minimum, by selecting the minimum supply voltage needed for the output required. The minimum supply voltage is important, because the internal power dissipation of a dc circuit is:

$$P = (V_S - V_{out})I_{out} + (|V_S| + |-V_S|)I_Q$$

where $I_{out}$ is output current, $I_Q$ is quiescent current, $V_{out}$ is output voltage, and $V_S$ and $-V_S$ are supply voltages.

Since output current and voltage are set for the application, the supply voltage is the only variable left to be controlled by the circuit designer. To exercise that option,




**2. Most hybrid power op amps work from a single dc supply, but their input signals must be biased 5 to 10 V above ground (a). An alternative hookup has a second low-voltage supply to maximize the unipolar output-voltage swing and allow ground-referenced inputs (b).**

the designer must stick to the minimum supply-to-output differential voltage as specified in the data sheet. Every 1-V increase in the differential results in a 1 W boost in dissipation for every 1 A of output current. Thus, anything that might add to the voltage differential, such as the use of an existing and convenient power supply, is not recommended.

On the other hand, tradeoffs for efficiency can be a very real consideration any time an op amp is powered by an unregulated supply, because the designer must not ignore line and load regulations, let alone ripple. So the design must include a voltage band above the minimum operating voltage needed for the required output. Any move above the bottom of that band heats up the op amp and reduces its ability to handle power.

#### DESIGNER'S CHOICE

A designer must thus choose between dissipating the unwanted power within the op amp itself or adding a separate dc regulator. As current increases, it is generally less expensive—in dollars per watt—to install a regulator.

In addition, unregulated supplies usually lack transient protection, which can result in faulty operation or damage, since power lines are notorious for their noise and voltage spikes. Worse, high-voltage, high-speed spikes pass right through power transformers and, on entering an electrolytic filter capacitor, encounter a high equivalent series resistance. A 1-kV spike on an incoming power line, for example, can easily make its way to the op amp's dc input pin. Line filters and zener clamps may prevent damage to the op amp, but they also cut down on the economies of using unregulated supplies.

Once the designer has selected an efficient way to deliver the minimum supply voltage needed by the power op amp, the next step is to cut IR losses by keeping the leads from the amplifier to supply and load as short as possible. At video frequencies, moreover, even a few inches of wire shows significant inductance, as well as the skin effect, which increases the wire's effective resistance. Multistrand (litz) wire is best for high-frequency circuits.

#### NONSYMMETRIC ADVANTAGES

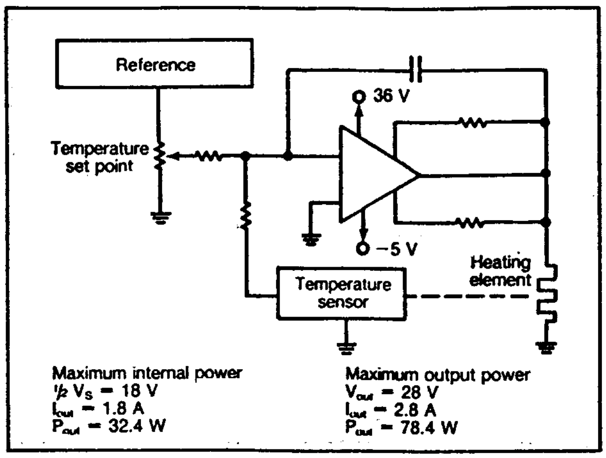
Designing an IC power amp to handle nonsymmetric output swings will also improve its output (Fig. 1). Symmetric power supplies, instead of the 26 V and −7 combination, increase dissipation substantially. Such a circuit requires an op amp with higher voltage and power ratings if output is to be maintained.

Most IC power op amps operate from a single supply voltage, but because common-mode operating specifications require the input to be 5 to 10 V away from either supply rail, a single supply demands that the input signals be biased in that way (Fig. 2a).

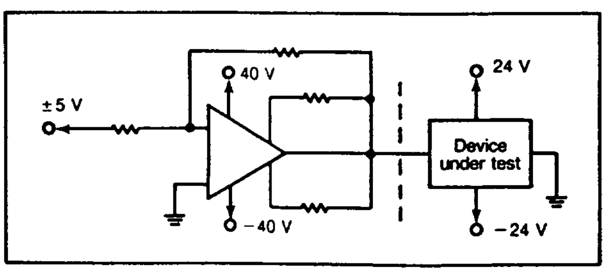
A second low-voltage supply can accept ground-referenced input signals as well as maximize the output's voltage swing in one direction (Fig. 2b). For resistive loads, for example, the 12-V supply only need deliver quiescent current to the op amp. On the other hand, if the load is reactive the 12-V supply must also absorb any reverse currents generated by the load's stored energy.

Although a load's power requirements are usually known ahead of time, calculating the op amp's internal dissipation is not always so easy. For purely resistive loads, the chip's maximum dissipation comes when the output voltage is half the supply voltage, a fact that can be valuable in making a worst-case analysis, provided that the op amp is not subjected to any short circuits.

A temperature controller, for example, is a purely resistive load driven by dc current (Fig. 3). Calculating the worst-case conditions ($V_{out} = V_S/2$) shows that the most power the op amp dissipates is 32.6 W. At full output, it delivers 78.4 W to a 10 Ω load.




**3. A purely resistive load driven with dc currents, such as in a temperature controller, embodies the simplest way to calculate worst-case power dissipation within a power op amp. Worst case occurs when output voltage is half supply voltage.**




**4. A complex example of worst-case power dissipation occurs when programmable power supplies are hit by short circuits in a device under test (DUT). The op amp is severely stressed if one of the DUT's 24-V supplies shorts while the programmable supply is at the opposite voltage.**

In a more complex situation, the programmable and fixed supplies are combined in an automated tester, and often have to tolerate short circuits in the device under test (Fig. 4). Worst-case dissipation occurs in such cases when one of the fixed supplies is shorted to a programmable supply set to the opposite voltage.

If the fixed supply's current limit is greater than that of the programmable supply, the latter will dissipate considerably more power than is normally encountered, even when its current-limiting feature takes effect. Internal dissipation by the programmable supply's op amp then equals the sum of its supply voltage and the fixed supply voltage, multiplied by the programmable supply's current limit.

### AC DIFFERENCES

But a power op amp handling ac creates a different set of circumstances. If the ac input signal's frequency is 60 Hz or more, the halfwave power-dissipation period will be shorter than the op amp's thermal time constant. Because only one transistor is on at a time, the effect of the thermal time constant results in a lower thermal resistance and a consequent increase in the amplifier's power-handling capability. If the input is sinusoidal and the load is resistive, the op amp's maximum internal rms power dissipation takes place when the peak output swings to 63.7% of the rail-to-rail supply voltage:

$$P_{max} = \frac{V_S^2}{2\pi^2 R_L}$$

where $V_S$ is total rail-to-rail supply voltage and $R_L$ is load resistance.

When the power op amp is driving a reactive load, a designer must account for the difference in phase between output voltage ($V_{out}$) and output current ($I_{out}$). Actual power dissipated may be several times that of equivalent resistive loads. In the worst case, a purely reactive load with a zero power factor, the op amp dissipates all power drawn from the supplies.

Reactive loads have a different, but equally simple, power-dissipation formula:

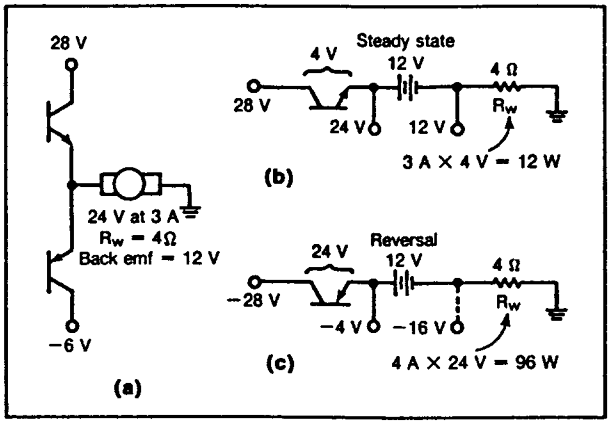
$$P = P_{in} - P_{out}$$

where $P_{in}$ is power drawn from the power supply and calculated from the dc supply voltages and the RMS supply currents, and $P_{out}$ is real power delivered to the load.

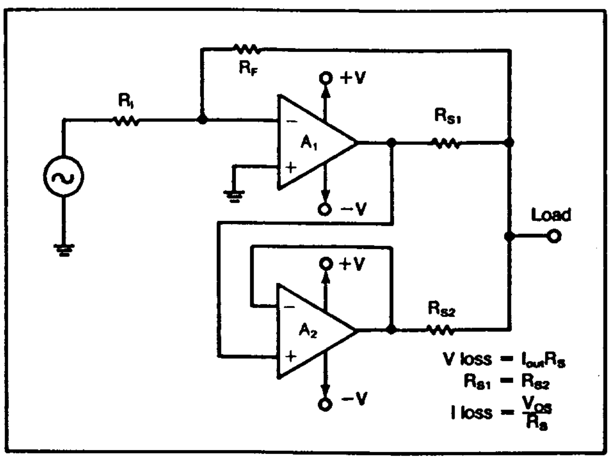
### MOTORS ARE MURDER

Motor control applications often confront a driving circuit with brutal demands, and a failure to anticipate them may prove fatal to the op amp. In one configuration, two output transistors from the op amp's control circuit drive the motor (Fig. 5a). Along with the motor's winding resistance and voltage rating, its back emf also helps determine the running current. Back emf can be modeled as a battery whose voltage is proportional to the motor's instantaneous velocity (Fig. 5b).

When the control circuit reverses the motor, the op amp quickly changes its output. But the motor's speed, and therefore its back emf, drops only as fast as the system's mechanical inertia allows. The initial effect is vastly different response times in the electronic and mechanical systems (Fig. 5c). As soon as the control circuit tries to reverse the motor, the op amp seeks to produce an output of −24 V. If it succeeded, it would throw a total of 36 V at 9 A across the motor's winding. What actually happens is that the output voltage depends on the op amp's current-limiting characteristic.




**5. A motor-drive control circuit using power op amps can place severe stress on the output transistors (a). Under steady-state running conditions only 4 V normally appears across the conducting device (b). When the motor reverses, however, that level shoots up to 24 V and the motor's back emf drives up the op amp's power dissipation (c).**




**6. Parallel operation of two power op amps increases the power available to the load. Sense resistors ($R_{S1}$, $R_{S2}$) ensure the load current is shared equally by the op amps. Using the smallest resistors possible minimizes loss of power through those resistors.**

A 4-A limit through the motor's winding results in a maximum drop across it of 16 V. With the 12-V back emf still in effect, output voltage is −4 V, so that 24 V appears across the op amp's conducting transistor and internal power dissipation briefly leaps to eight times that for steady-state operation.

One way to deliver more power without exceeding that used for steady-state operation is to keep the drive voltage from reversing before the motor's mechanical inertia has run down. In that way, by avoiding extremely high dissipation, speed of reversal is traded for higher torque.

### MULTIPLE OPTIONS

When one op amp cannot meet heavy-duty demands, several can be teamed up in a bridge circuit to share the burden. Benefits of that arrangement include doubling output power and voltage, halving power supply needs, driving a bidirectional output from the one supply, and doubling the slew rate.

A bridge circuit spans the difference between load-power needs and the limitations imposed by power supplies or op amps. The advantages of this kind of circuit usually outweigh the cost and complexity of the extra components.

Parallel operation also increases the output current and power to the load. However, the low output impedance of power op amps prevents their connection in parallel without modification. For example, placing a small sense resistor, $R_{S1}$, within the feedback loop of an uncommitted master amplifier, $A_1$, maintains accuracy (Fig. 6). A slave amplifier, $A_2$, functions as a unity-gain buffer and the two amplifiers' output voltages thus become equal. With two identical sense resistors ($R_{S1} = R_{S2}$), the amplifiers share load current equally.

When selecting sense resistors, the designer has two factors to consider. One is that the output current produces a voltage drop across the resistors, which mandates a higher voltage supply; the other, that the slave amplifier's voltage offset appears across the sum of the two sense resistors. A small current will thus circulate only between the two amplifiers, which does waste some power.

### DUMP THE HEAT

To help in mounting and heatsinking, most power op amp packages are isolated from the internal electrical circuits, otherwise the use of insulating washers will likely add thermal resistance to the case-to-heat sink interface.

Typical thermal resistance of 5.7-mil mica or 2-mil kapton washers with a common 8-pin TO-3 package is 0.8°C/W—as opposed to 0.2°C/W without a washer—

using thermal joint compound in all cases.

The op amp must, of course, be mounted directly on the heat sink to gain maximum dissipation, and the bigger the heat sink the more power it will let go. At high power levels, a large heat sink is often more economical than a large op amp.

Forced-air or even liquid cooling can reduce the need for a large heat sink. The former type of cooling is easier to install but usually no more than doubles the cooling effect of a simple convection heat sink. Higher power levels render liquid cooling the more attractive choice.

Typical heat-sink ratings for a 6 in.$^2$ area, 2 in. high are 0.85°C/W for convection, 0.5°C/W for forced air, and 0.05°C/W for liquid cooling. As a precaution, screws with spring washers help keep large op amps and their heat sinks firmly in place. Otherwise cyclic changes in temperature may loosen the mounting and increase thermal resistance.

### SENSIBLE SHUTDOWN

It often makes sense to have an overworked power op amp shut down automatically, rather than to beef up the circuit or drain off the heat. Such internal thermal protection, which shuts the component down if the substrate temperature exceeds safe limits, increases the output power normally available. Because destructive temperatures never build up, a circuit's design can be shaped entirely according to normal operating conditions.

Automatic shutdown is especially suitable for programmable power supplies where the output is the normal operating voltage of a device under test. If the device is defective, and the programmable supply output consequently shorts to ground, the automatic shutdown cuts the power before any damage can take place, either to the supply or to the load.

However, automatic thermal shutdown is not a cure-all, nor does it provide the designer with a license to disregard secondary breakdown curves that define a power op amp's safe operating area. Unless the manufacturer states otherwise, the time constant for automatic shutdown should be reckoned at 250 to 500 ms. Even during that interval, worst-case power levels must not exceed the steady-state secondary breakdown value given in the published safe operating-area curve.□

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| How valuable? | Circle |
|---|---|
| Highly | 548 |
| Moderately | 549 |
| Slightly | 550 |